ECE 340 Lectures 27
Semiconductor Electronics

Spring 2022
10:00-10:50am
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2062 ECE Building

Today's Discussion

- ***p-n*** **junctions are not just rectifiers!**
- **Review of optoelectronic devices (part 1)**
  - **Illuminated Junction**
  - **Solar Cells**
  - **Photodetectors**

Exercise (from previous class)

- **Consider an abrupt *p-n* junction with cross-sectional area A = 1 mm² at T = 300K, with:**

p-side	*n*-side
$N_A = 10^{16}\text{cm}^{-3}$	$N_D = 10^{18}\text{cm}^{-3}$
$\mu_p = 370\text{cm}^2/\text{Vs}$	$\mu_n = 550\text{cm}^2/\text{Vs}$
$\mu_n = 1{,}000\text{cm}^2/\text{Vs}$	$\mu_p = 150\text{cm}^2/\text{Vs}$
$\tau_n = 1.0\ \mu s$	$\tau_p = 1.0\ \mu s$

- **Find the reverse saturation current (done earlier)**
- **Find the junction (depletion) capacitance at $-5V$**

Exercise (now calculate capacitance)

- **Capacitance at $-5V$**

$$V_0 = \frac{k_B T}{q} \ln \frac{p_p}{p_n} = 0.0259 \times \ln \frac{10^{16}}{2.25 \times 10^2} = 0.8139 \text{ V}$$

One-sided *p-n*+ junction

$$C_j = \epsilon A \sqrt{\frac{q}{2\epsilon(V_0 - V)} \frac{N_D N_A}{N_A + N_D}} = \sqrt{\epsilon} A \sqrt{\frac{q N_A}{2(V_0 - V)}}$$

$$= \sqrt{8.85 \times 10^{-14} \times 11.8} \times 10^{-2} \sqrt{\frac{1.6 \times 10^{-19} \times 10^{16}}{2(0.8139 + 5)}}$$

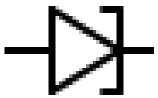
$$= 1.199 \times 10^{-10} \text{ F}$$

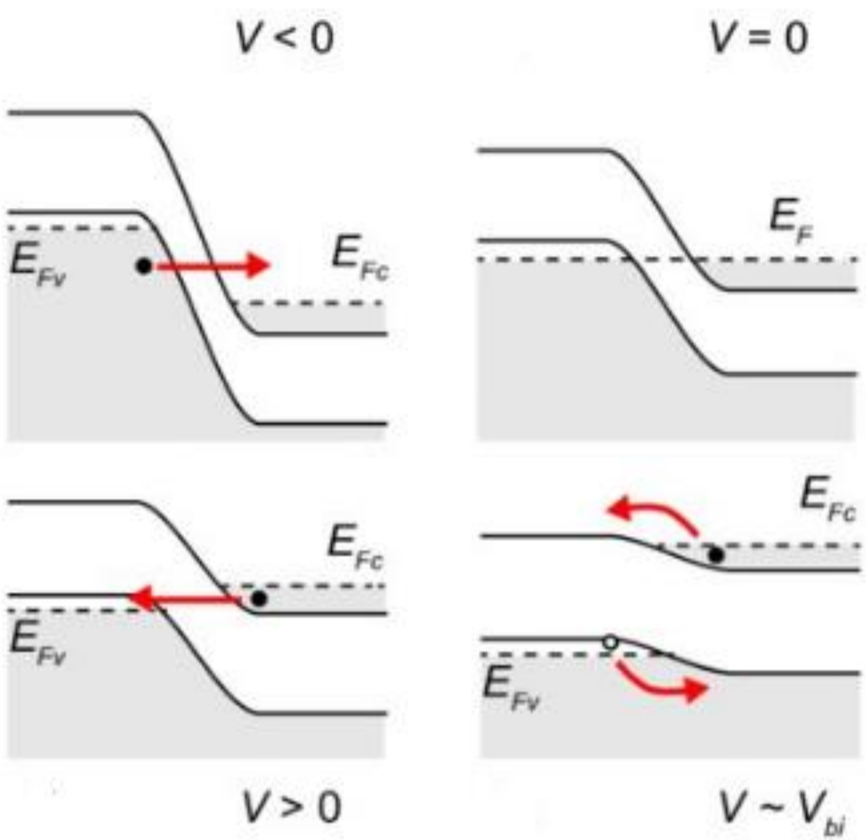
p-n junctions are not just rectifiers!

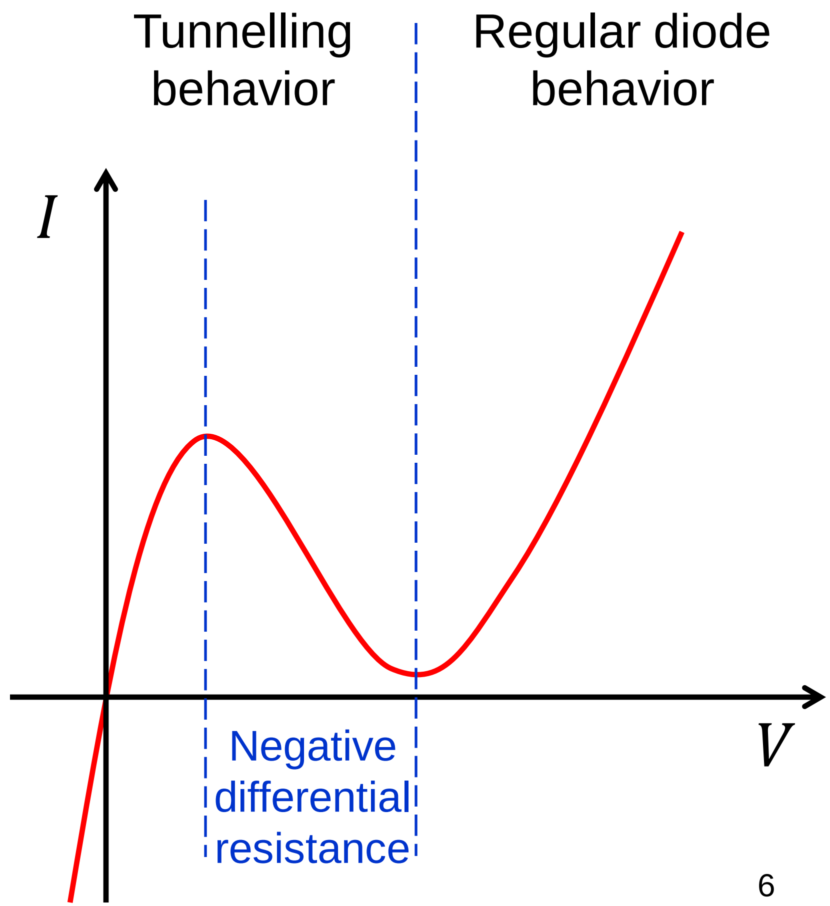
- **Besides rectifiers and capacitors, specialized *p-n* junction structures make**
  - **Solid state lasers**
  - **Light emitting diodes (LED)**
  - **Photodetectors**
  - **Solar cells**
  - **and even microwave amplifiers (tunnel diode, see next)**

EXTRA – Tunnel diode (Esaki, Nobel Prize 1973)

- **Very heavily doped on both sides**

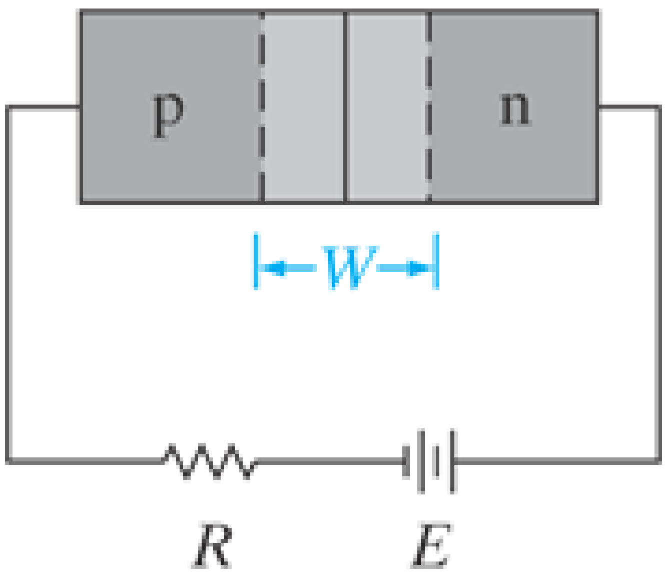


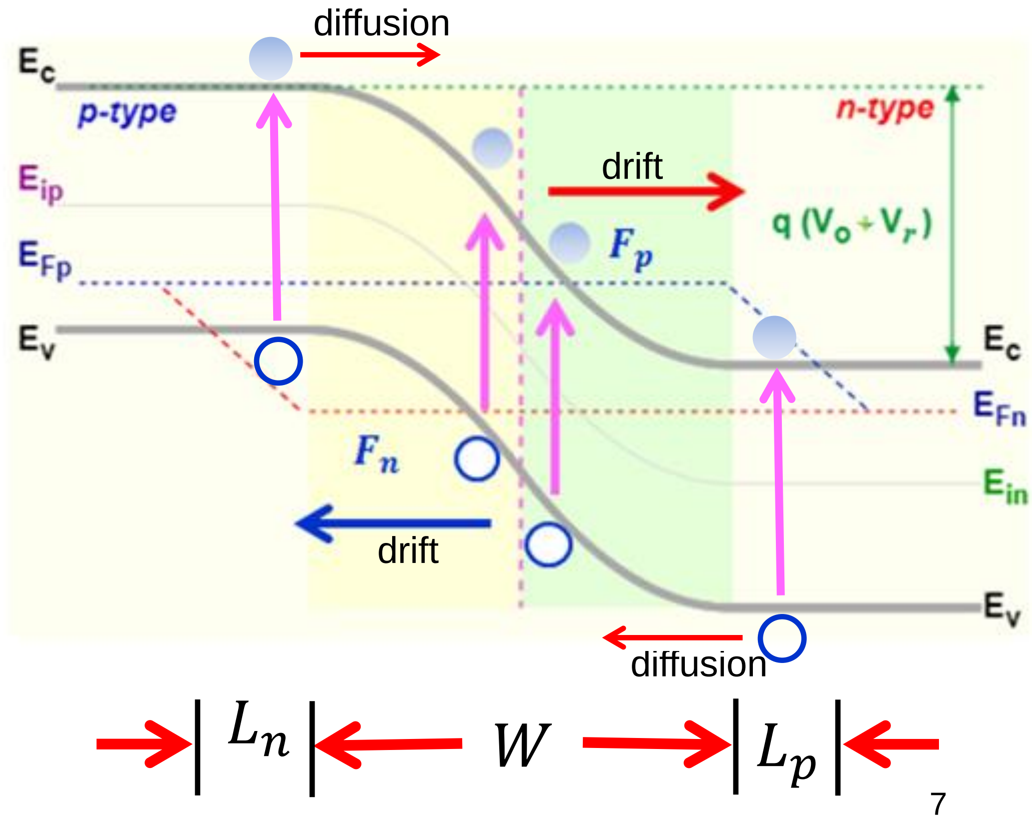




Thermal generation

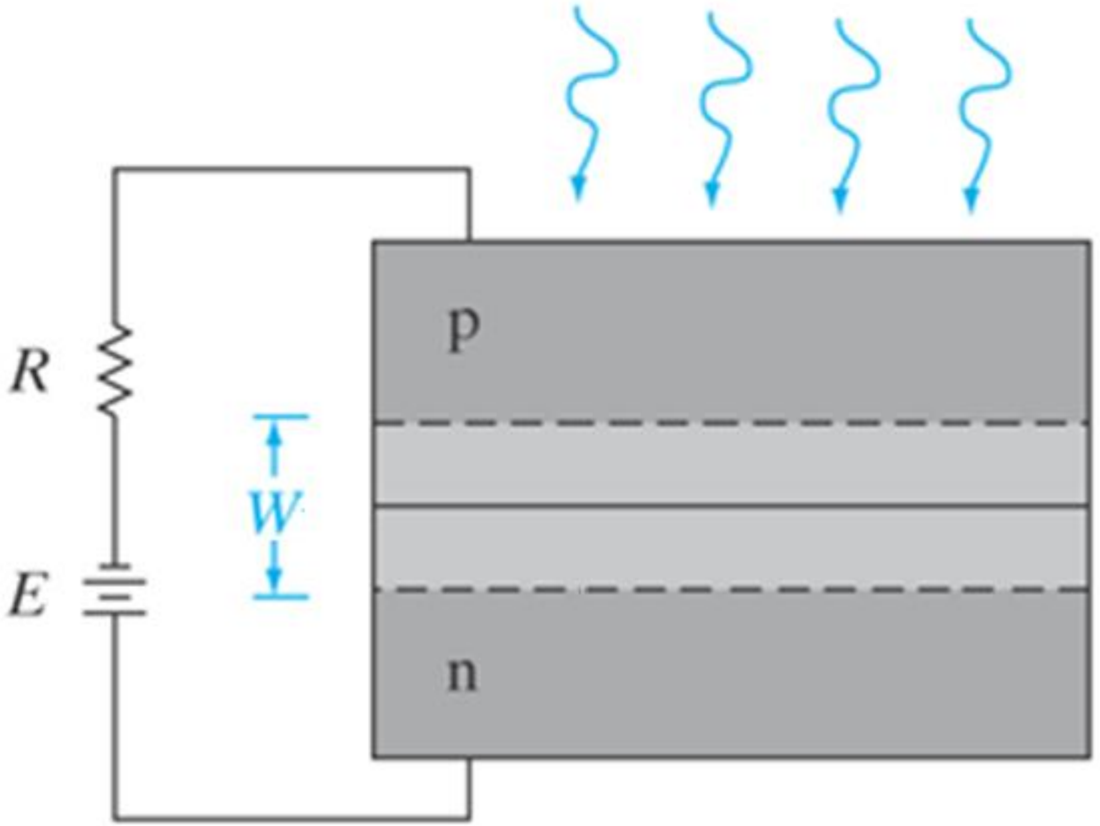
Minority carriers generated thermally within a diffusion length on each side of the depletion region are swept to the other side by the field.





Optoelectronics devices - Photodiode

- **Illuminated junction**

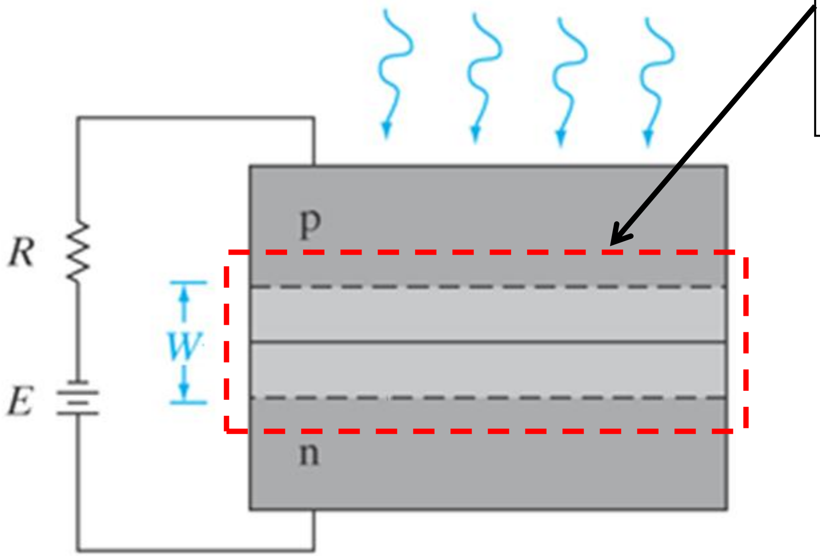


Optoelectronics devices - Photodiode

- **Illuminated junction**

$$h\nu > E_g$$

Carriers generated optically in the depletion region and in the adjacent diffusion lengths are also separated by the junction field.



$$I_{op} = qAg_{op}\left(L_p + L_n + W\right)$$

Photodiode current

$$I = I_0\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right] - I_{op}$$

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right]$$

$$-qAg_{op}\left(L_p + L_n + W\right)$$

Note: $L_p = \sqrt{D_p \tau_p}$ and $L_n = \sqrt{D_n \tau_n}$

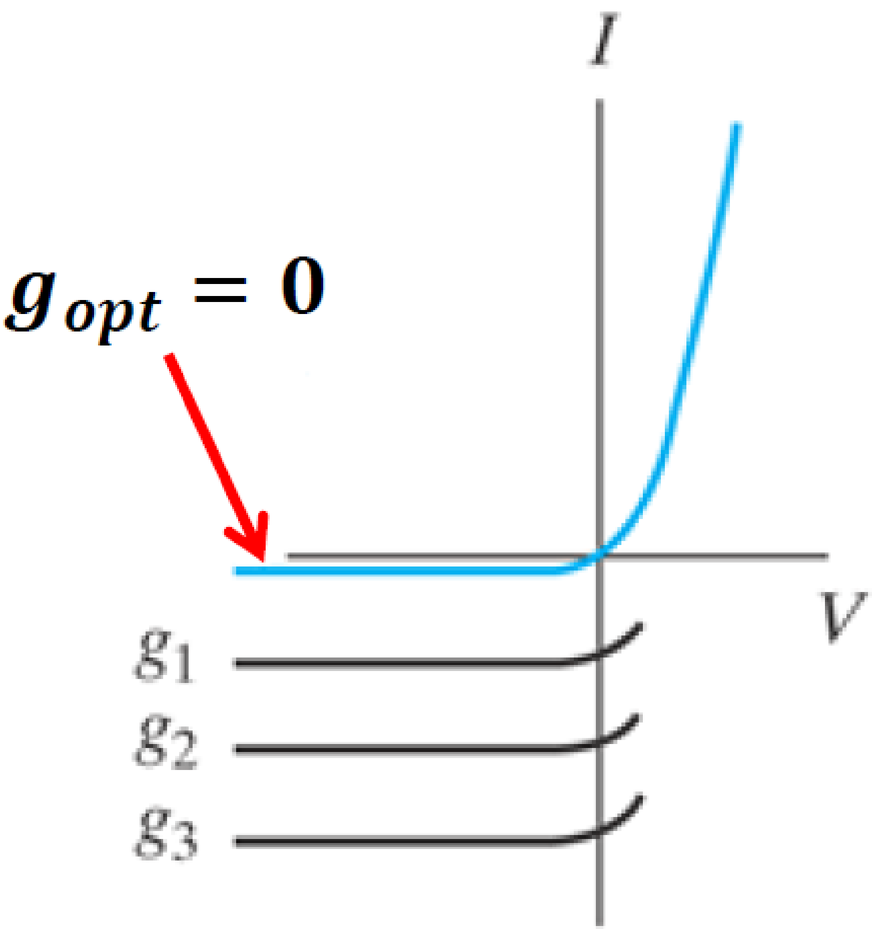
$$I_0 = \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p$$

$$= \frac{D_p}{\sqrt{D_p \tau_p}} p_n + \frac{D_n}{\sqrt{D_n \tau_n}} n_p$$

$$= \frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p$$

Photodiode – Photoconductive mode (reverse bias)

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - qAg_{op}(L_p + L_n + W)$$

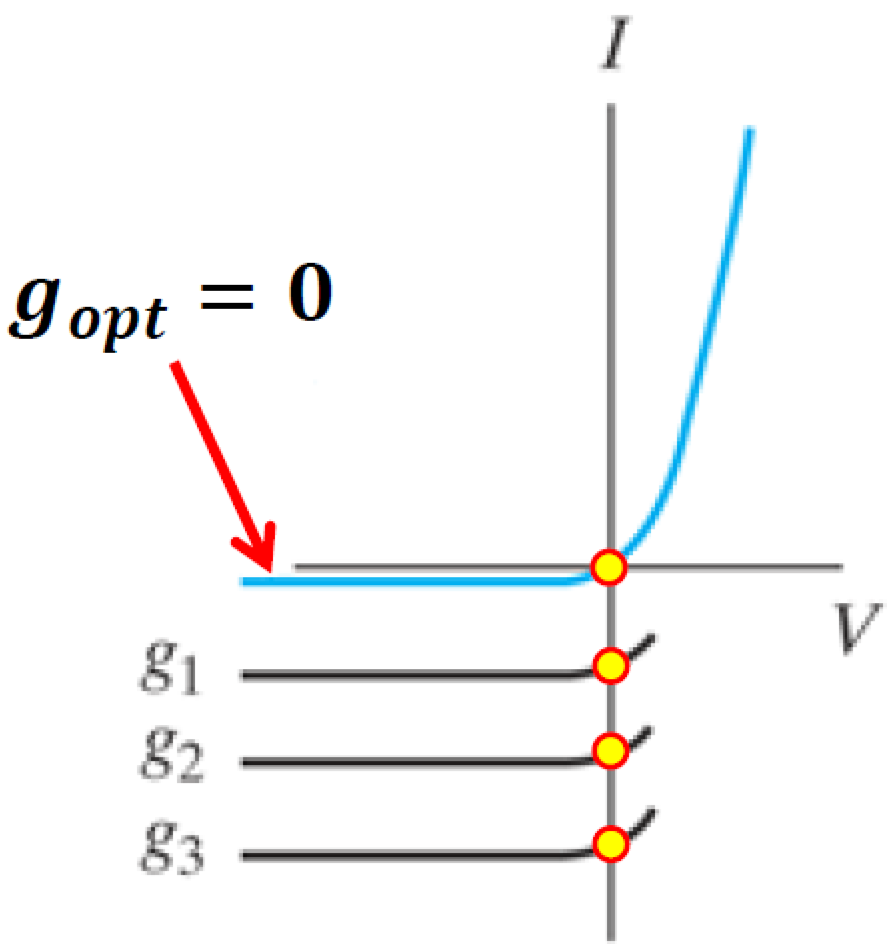


$$g_3 > g_2 > g_1$$

optical generation lowers the ***I-V*** curve

Photodiode – Photoconductive mode (reverse bias)

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - qAg_{op}(L_p + L_n + W)$$



short circuit current

NOTE: V is the voltage at the ends of the diode, not the battery

Photodiode voltage – Photovoltaic mode

$$I = I_0\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - I_{op} = 0 \Rightarrow V_{oc} = \frac{k_BT}{q}\ln\left(\frac{I_{op}}{I_0} + 1\right) \Rightarrow$$

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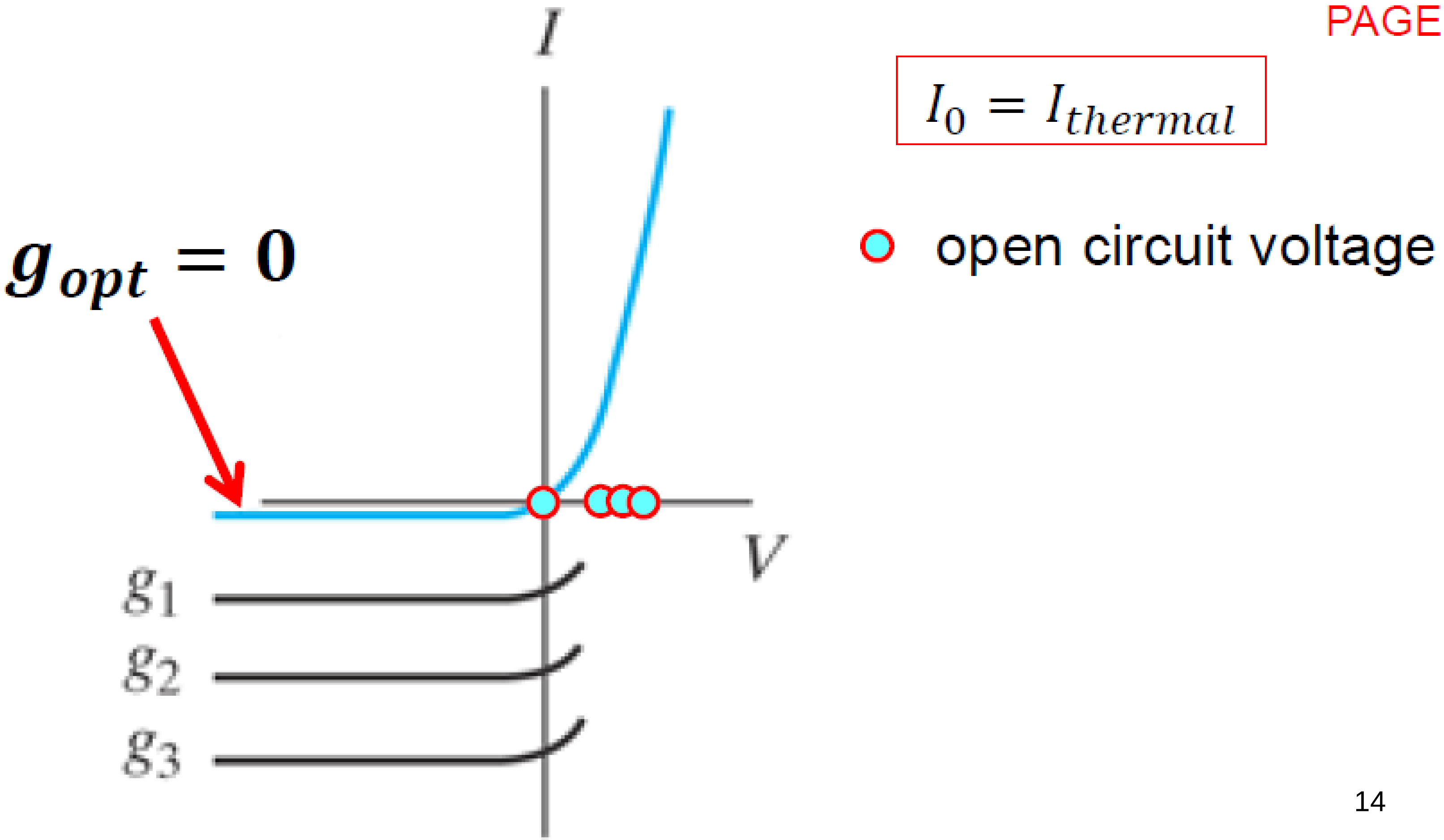
$$I_0 = I_{thermal}$$



Photodiode voltage

open circuit voltage

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{I_{op}}{I_0} + 1\right) =$$

$$= \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + W}{\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p} g_{op} + 1\right)$$

Photodiode voltage

open circuit voltage – symmetrical junction

$$p_n = n_p;\ \tau_n = \tau_p; \quad g_{th} = \frac{p_n}{\tau_n}$$

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + W}{\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p} g_{op} + 1 \right)$$

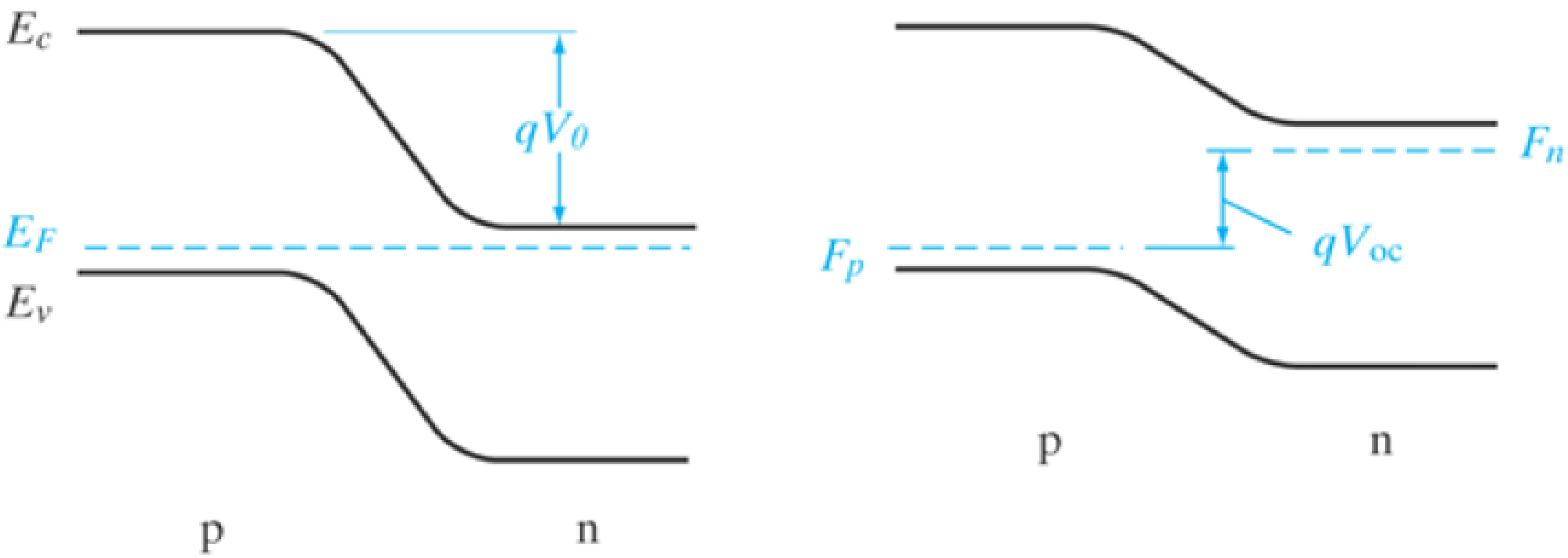
if generation inside
W can be neglected

If $g_{op} \gg g_{th}$

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + \cancel{W}}{(L_p + L_n) g_{th}} g_{op} + 1 \right) = \frac{k_B T}{q} \ln\left(\frac{g_{op}}{g_{th}} + \cancel{1} \right)$$

Open circuit voltage

Fermi level splits into quasi-Fermi levels

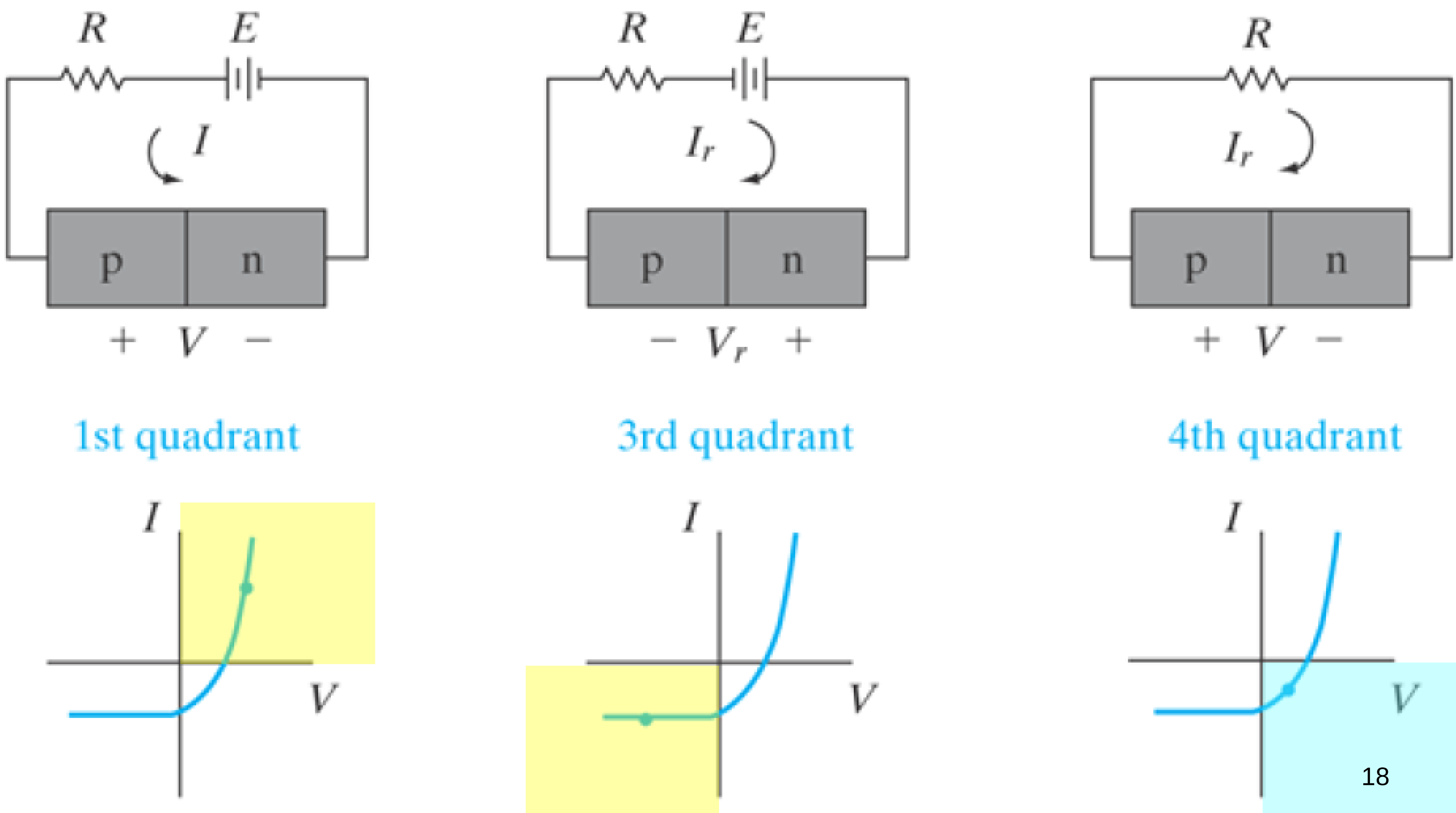


Limit to qV_{oc} is the contact potential qV_o

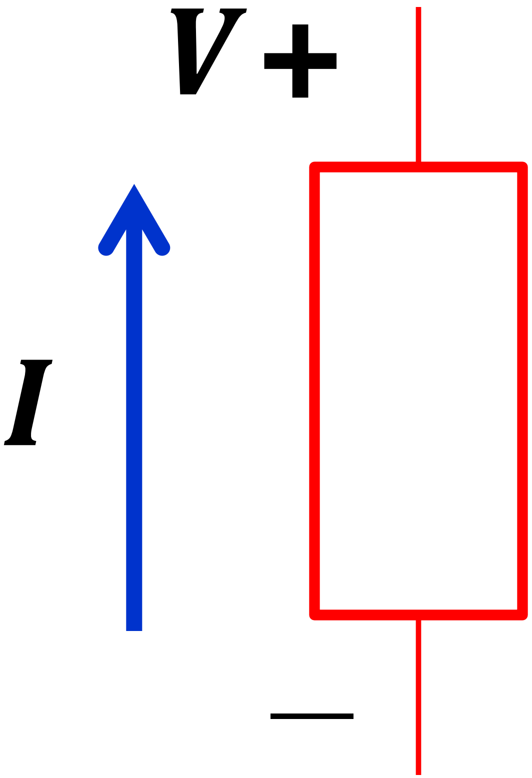
Operation of illuminated junction

power delivered to junction by external circuit

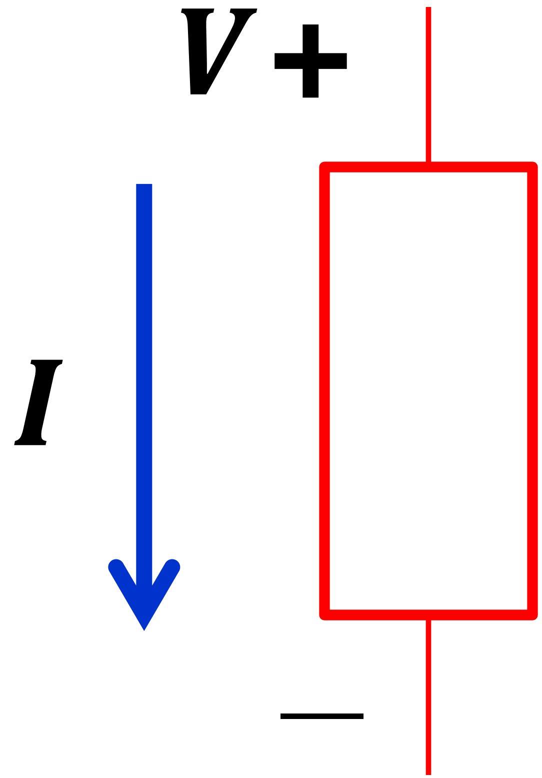
power delivered to load by junction



Remember:

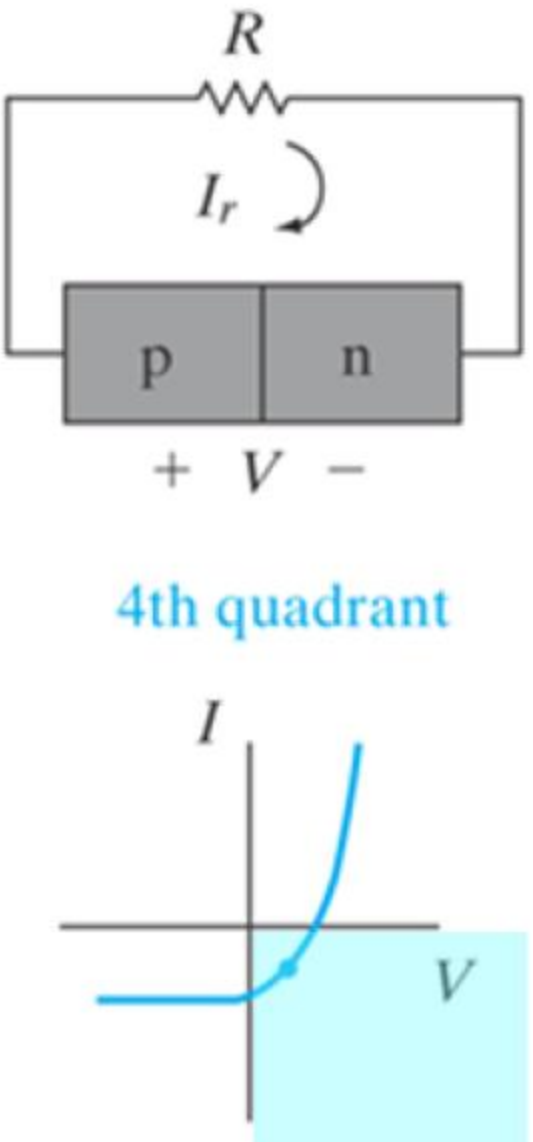


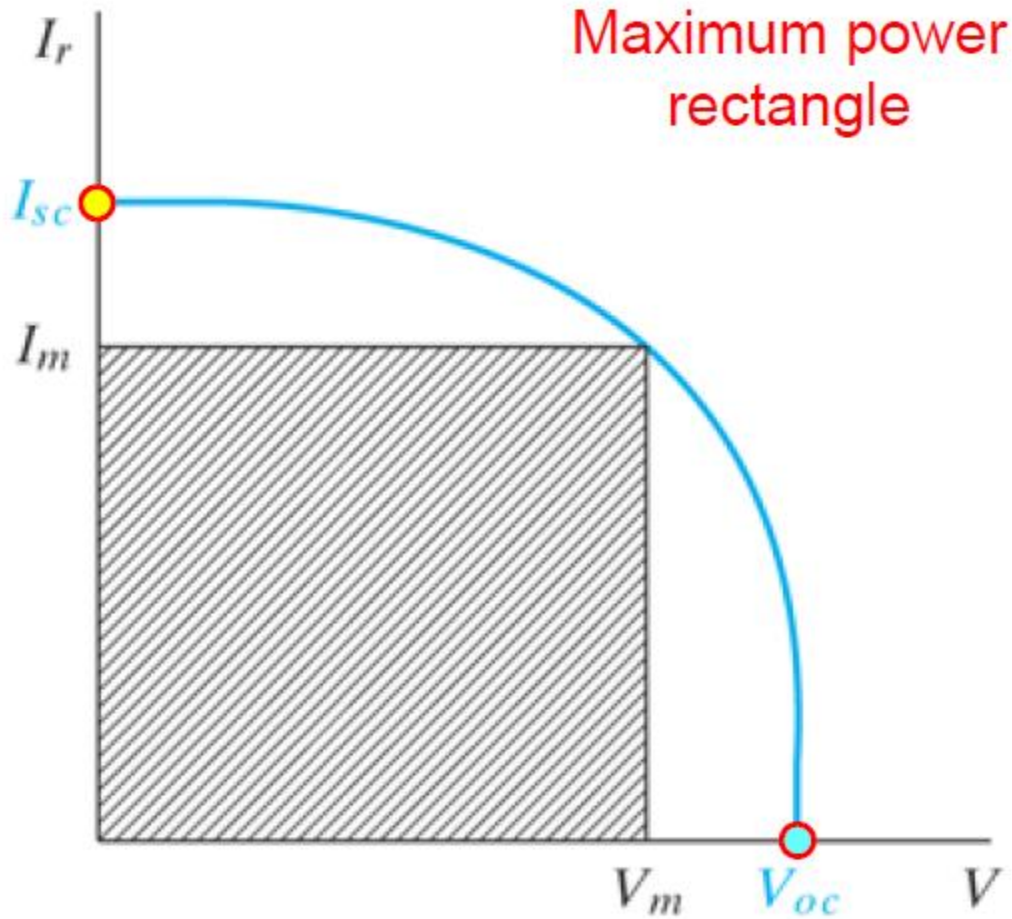
Element provides power
(source)



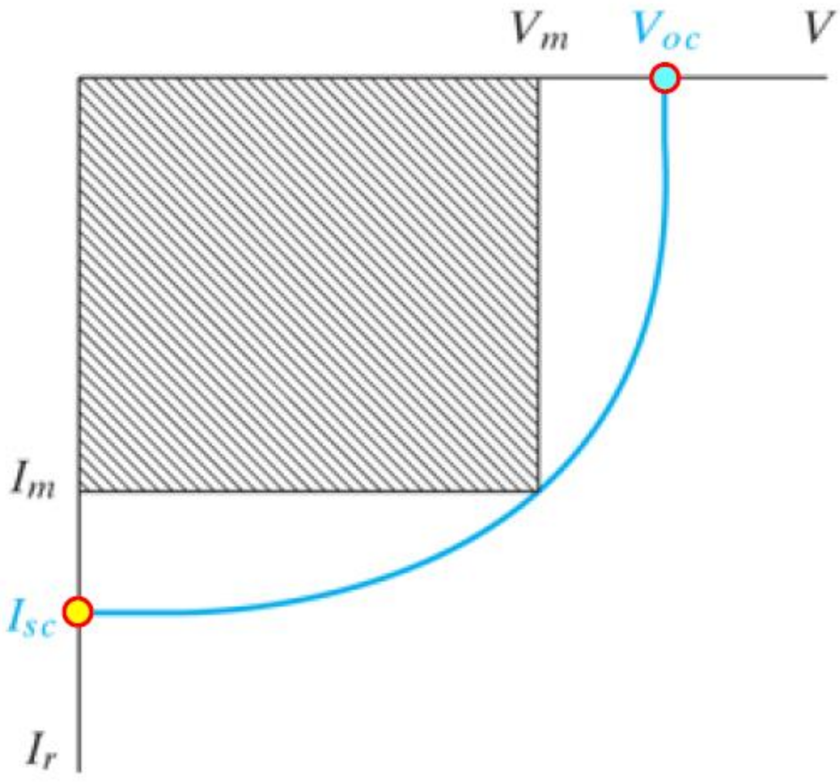
Element consumes power
(e.g., resistive)

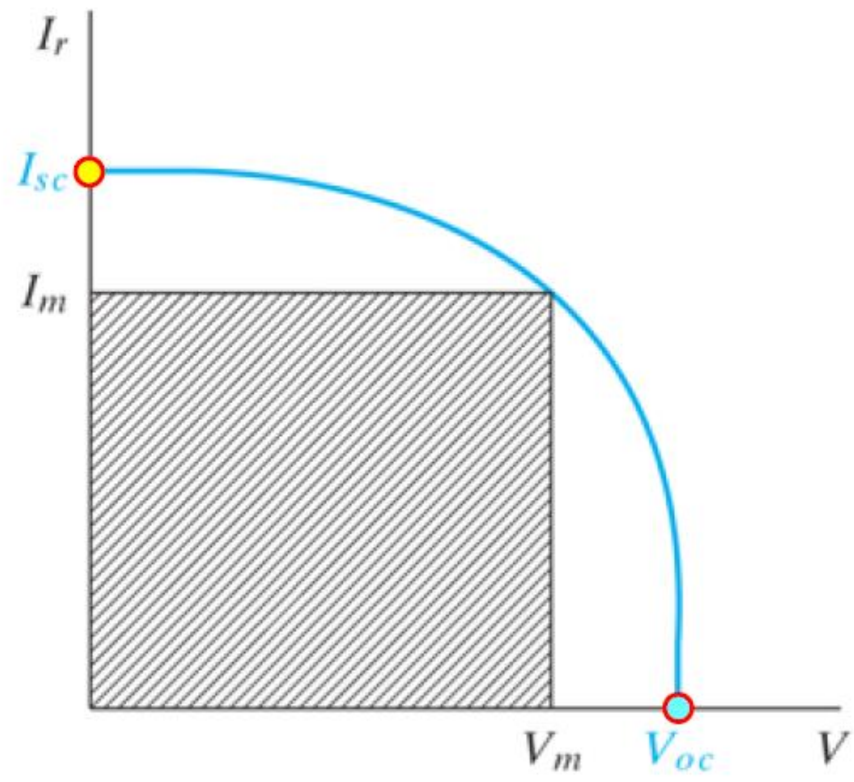
Solar cell – photovoltaic mode



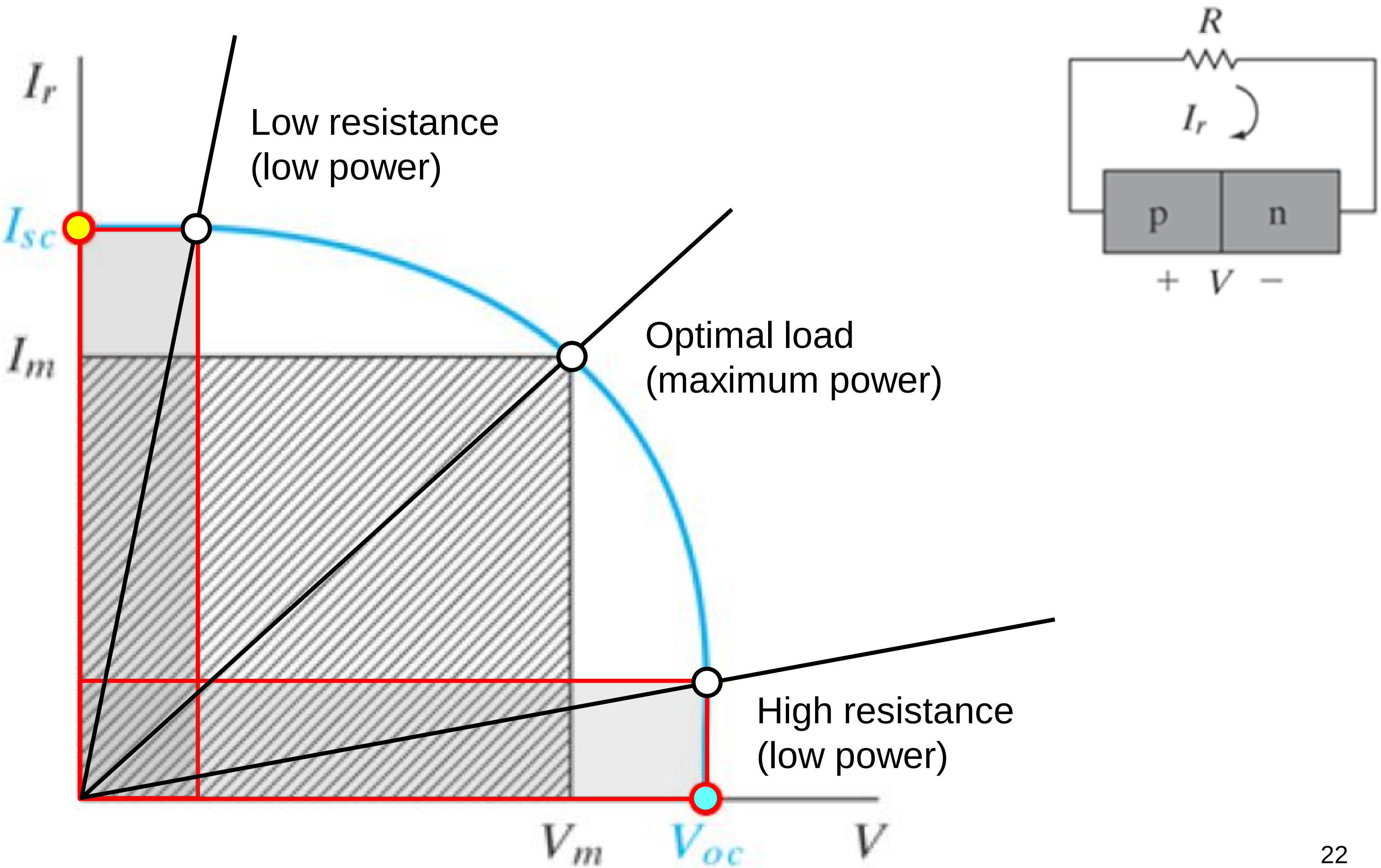


NOTE: you may find this diagram plotted either way





Maximum power requires optimal load



Solar cell - Example

A solar cell has short-circuit current of 100 mA and open circuit voltage of 0.8 V under full solar illumination. With a fill-factor 0.7 what is the maximum power delivered to a load by the cell?

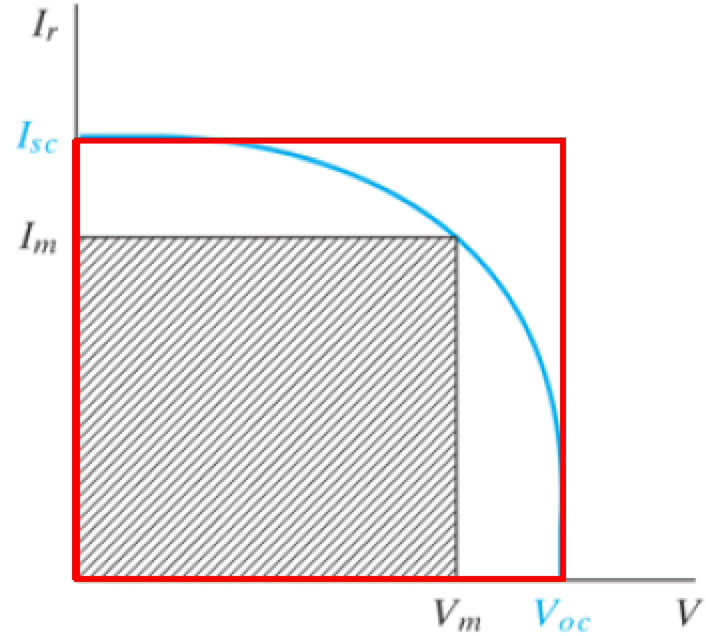
$$\frac{V_M \times I_M}{V_{oc} \times I_{sc}} = \text{Fill Factor}$$

$$P_{max} = V_M \times I_M =$$

$$= (V_{oc} \times I_{sc}) \times \text{Fill Factor}$$

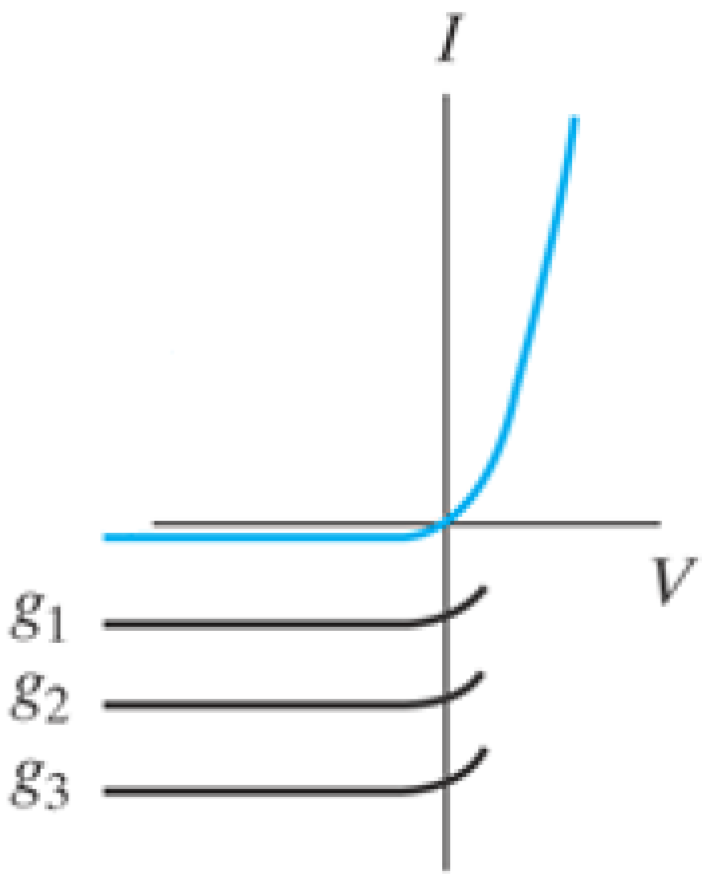
$$= (0.8 \times 100m) \times 0.7$$

$$= 0.056W = 56mW$$



Photodetectors

When operated in third quadrant, the current through the photodiode is essentially independent of voltage and proportional to the optical generation rate.



If we want to use the photodiode to detect optical communications then speed of generated carrier collection is important to have large bandwidth.

(Larger bandwith = more customers accommodated in the same channel)

Photodetectors

Carrier diffusion is a slow process.

Best situation if most of the carriers are generated in the high-field depletion region (depletion layer photodiode)

Wide depletion layer = High sensitivity

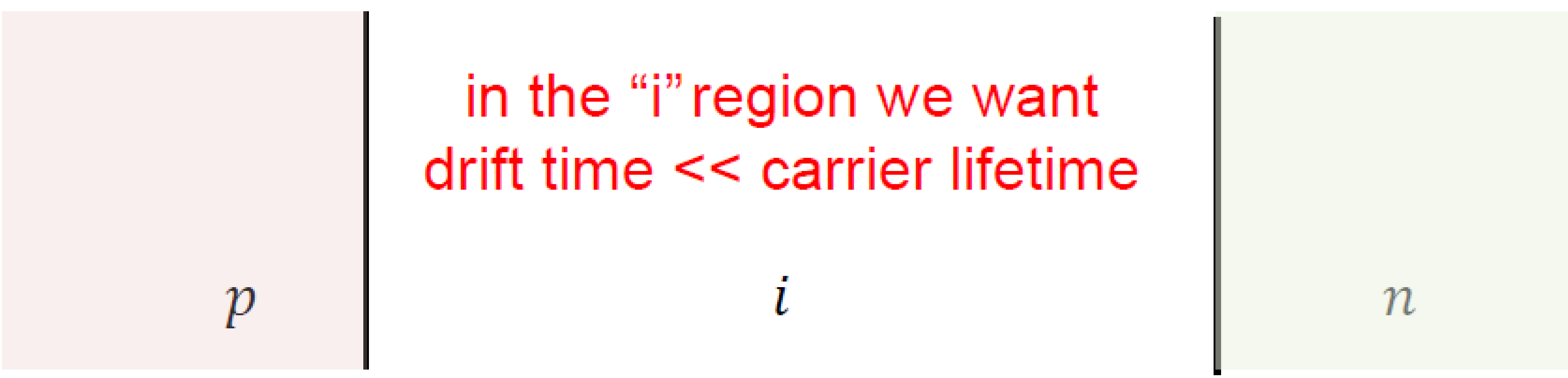
ADVANTAGE: A wide junction has lower capacitance (remember the previous lecture?). Good for RC constant and speed.

POTENTIAL DRAWBACK: If the depletion region is too wide, it may take too long for carriers to traverse it, which may affect adversely the bandwidth.

p-i-n photodetector

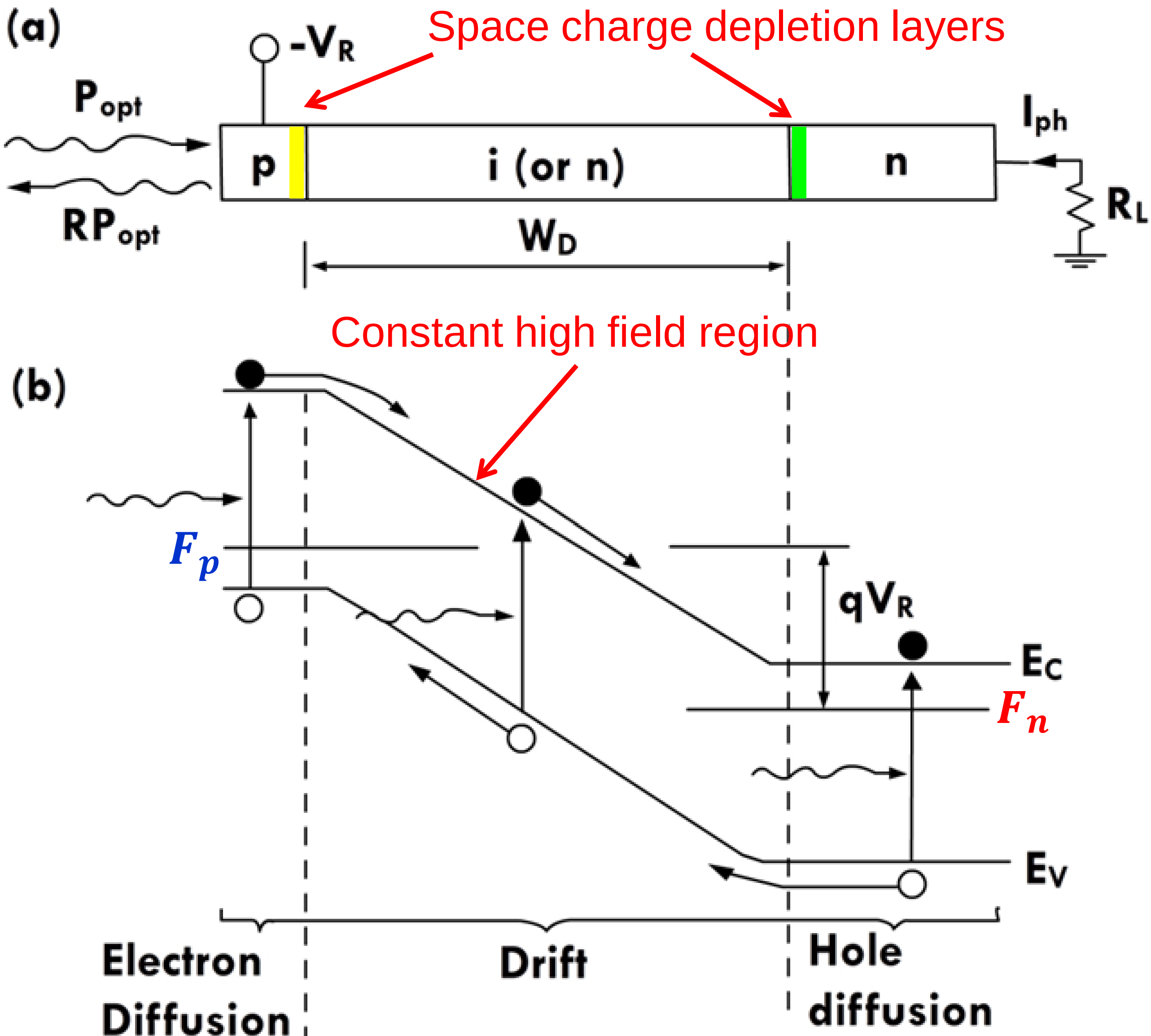
A low doped region is sandwiched between *p* and *n* sides (the "i" stands for intrinsic. There may be some doping but important thing is to have a high resistivity).

In reverse bias, most of the voltage drops across the high resistivity "i" region.



so most carriers generated are collected by the *p* and *n* regions

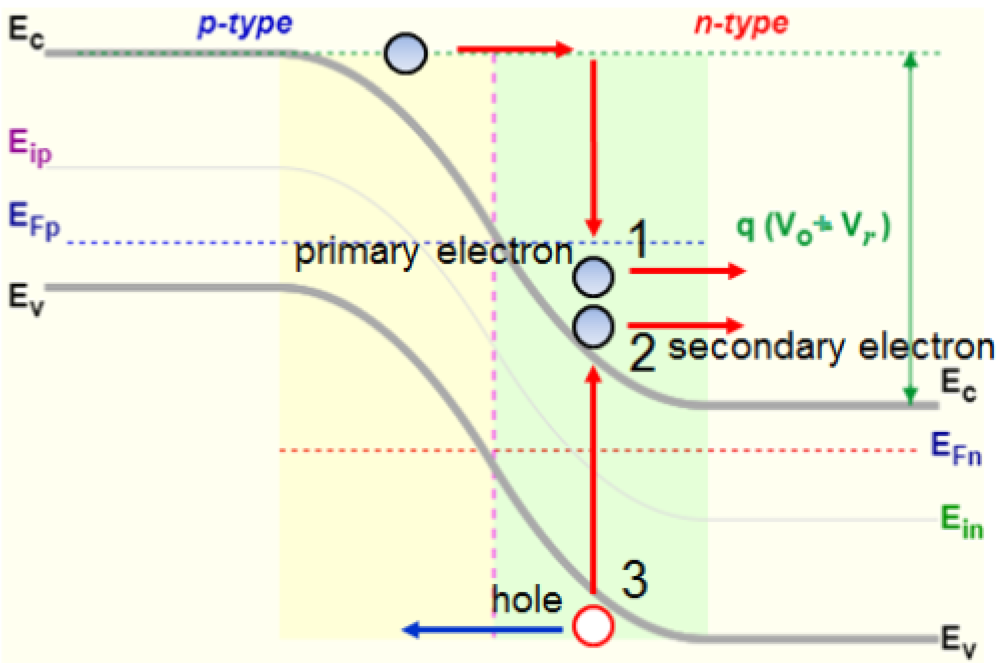
p-i-n photodetector



Avalanche Photodiode (APD)

Consists of a p-n junction in reverse bias operated in *breakdown conditions*.

Each photogenerated carrier has the chance to generate EHP by impact ionization. By avalanche multiplication, the signal is essentially amplified.



Avalanche Photodiode (APD)

APD's are very sensitive, but noise can be a problem because of the randomness of the generation by impact ionization process.

The bandgap of the material is tailored to the optical frequencies to be detected so that generated carriers have similar energies. Creation of the material system follows *bandgap engineering* design procedures, using compound III-V semiconductors.

APD's are very useful for long distance optical fiber communication systems.

Quantum Efficiency

This is an important figure of merit of photodetectors:

How many carriers are collected per incoming photon of energy $h\nu$?

$$\frac{Photocurrent\ density}{electron\ charge} = \frac{J_{op}}{q} = \#\ carriers/\mathrm{s}$$

$$\frac{Incident\ optical\ power\ density}{energy\ of\ a\ photon} = \frac{P_{op}}{h\nu} = \#\ photons/\mathrm{s}$$

$$\eta_Q = \frac{J_{op}}{q} \Big/ \frac{P_{op}}{h\nu} = quantum\ efficiency$$